Part I

Radiative Budget and Greenhouse Effect

H. Chepfer, M. Chiriaco, V. Noel

The Earth receives its energy from the Sun. The Earth atmosphere and surface (ocean/continent) absorb/emit and reflect the Sun radiation, leading to an equilibrium temperature of about 15°C in annual mean all over the globe. The goal of this course is to obtain basic knowledge on radiation exchanges and greenhouse effect in the Earth system. What would be the Earth temperature in absence of atmosphere? in presence of an atmosphere absorbing all radiation from the Sun? What are the key modulators of the Earth Radiative Budget? How does it change with latitude and time (seasons, hours)? How do we measure radiations?

This course is divided into 2 parts:

1. Lecture on radiative budget and greenhouse effect (H. Chepfer)

2. One practical class to be chosen among the two following topics:
   2.a. Shortwave radiations (H. Chepfer, V. Noel)
   2.b. Long-wave radiations (M. Chiriaco)

The two tutorials will use measurements collected at the SIRTA[1] observatory.

A summary will be prepared at the end of the day for the evening presentation and discussion session (day 1).

[1] SIRTA stands for Site Instrumental de Recherche par Télédétection Atmosphérique. It is a French national atmospheric observatory dedicated to cloud and aerosol research. SIRTA is located in Palaiseau (49N, 2E), 20 km south of Paris (France) in a semi-urban environment. The observatory gathers and operates a suite of state-of-the-art active and passive remote sensing instruments from a large community to document and monitor an ensemble of radiative and dynamic processes in the atmosphere. SIRTA is an observatory of Institut Pierre Simon Laplace (IPSL), a French research institute in environmental sciences. It is hosted by Ecole Polytechnique and supported by Institut National des Sciences de l'Univers (INSU/CNRS), Centre National d'Etudes Spatiales (CNES), Centre d'Enseignement et de Recherche en Environnement Atmosphérique (CEREA).

Radiative Budget and Greenhouse Effect

Lecture by

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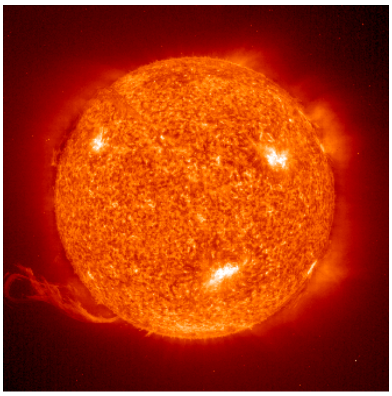
contributions from JL. Dufresne, K. Laval, S. Bony

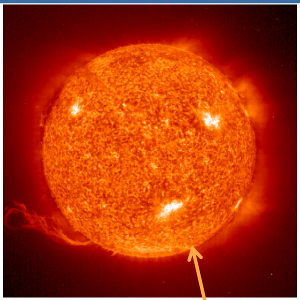


Solar radiation is the only source of heating for the Earth at the considered time scale (years, hundreds of years)

Without the atmosphere: T_{Earth} = -18°C

In reality, T_{Earth} = + 15°C because of:
- Natural greenhouse effect (+30°C)
- Convection (avoid excess heat)

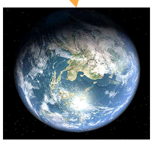
Radiative Budget and Greenhouse Effect



Sun Radius :
695 500 km

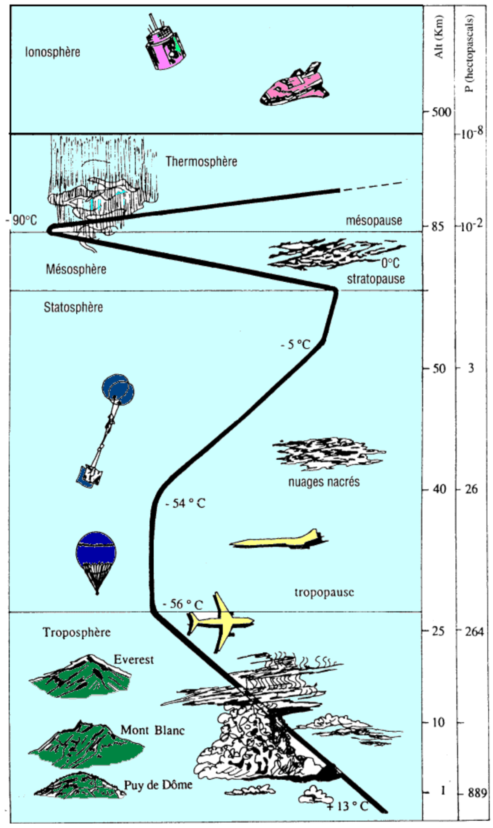
Distance Earth-Sun:
150 000 000 km

Earth Radius:
6 378 km

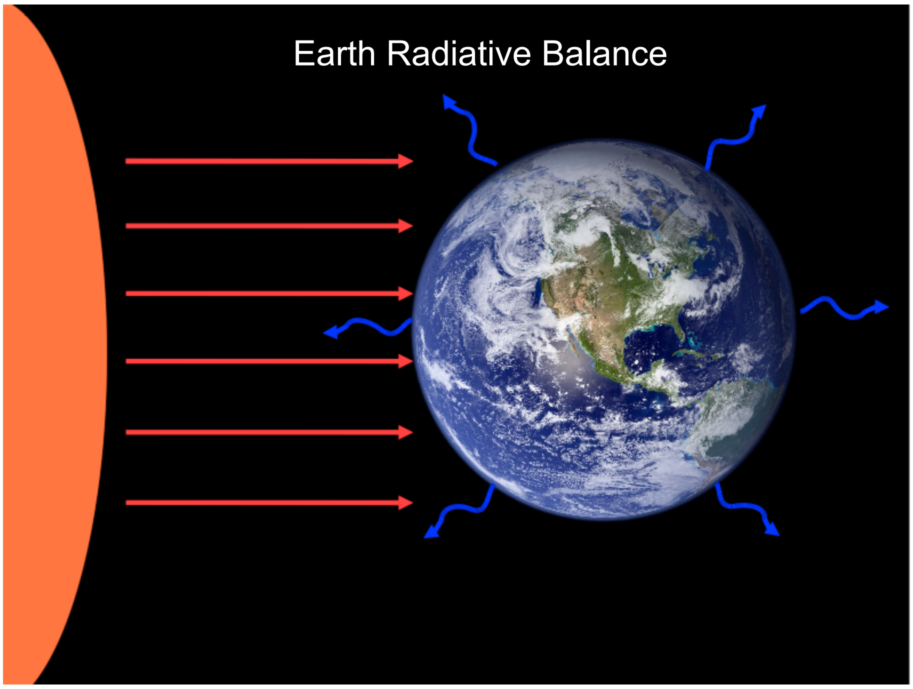


The Earth Atmosphere:

a thin layer which weight is concentrated in about *20 km* of thickness.



Radiative Budget and Greenhouse Effect



In average over a year and the globe, the Earth emits all the radiation received:
the radiative budget is balanced

Course Plan

1) Radiation: basic notions
   - Emission of radiation
   - Albedo and reflected radiation
   - Temperature equilibrium

2) Greenhouse effect

3) Earth radiative budget

4) Very simple formulation of the radiative budget

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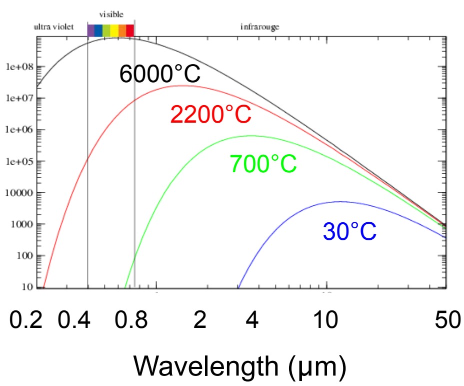
1) Radiation: basics

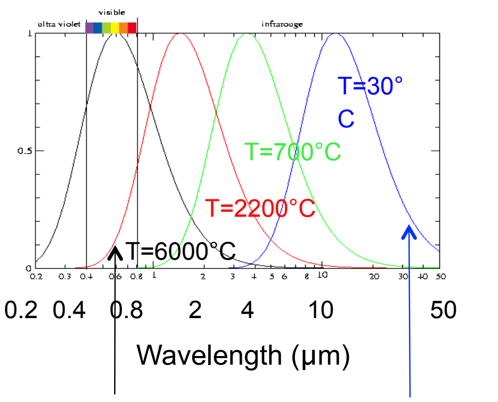
Emission of radiation:
all bodies emit radiation
its intensity and wavelength depend on the body temperature

Emitted Energy



Sun (about 6000°C)
Light bulb (2200°C)
Volcano lava (700°C)
Earth (about 30°C)

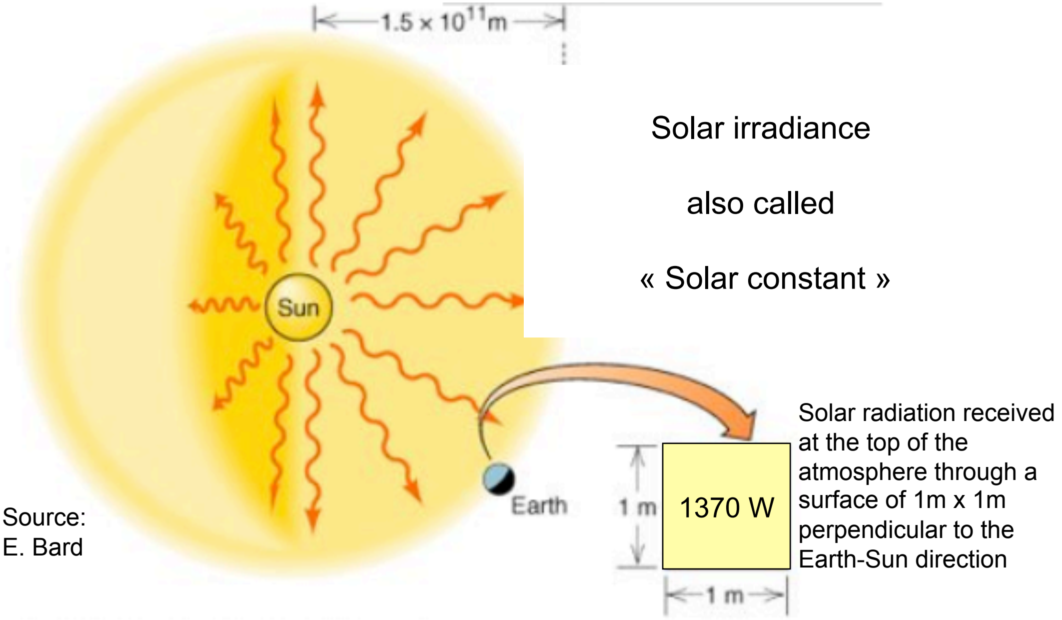
Normalized Emitted Energy



Separation of emission spectrum
Sun emission: mostly Short-wave
Earth emission: mostly Long-wave

Radiative Budget and Greenhouse Effect

The Sun produces the energy at the origin of the dynamical motions of the atmosphere and the ocean



Half of the Earth is in the night => 342 W/m2 for one day all over the globe

Radiative Budget and Greenhouse Effect

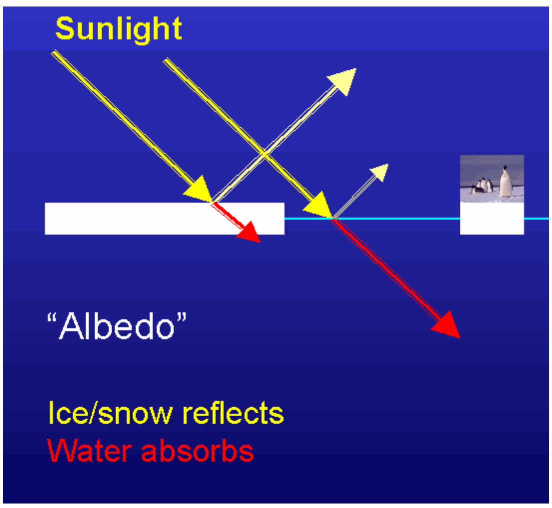
Albedo and reflected radiation

Albedo – from latin « whiteness »: Parasol effect

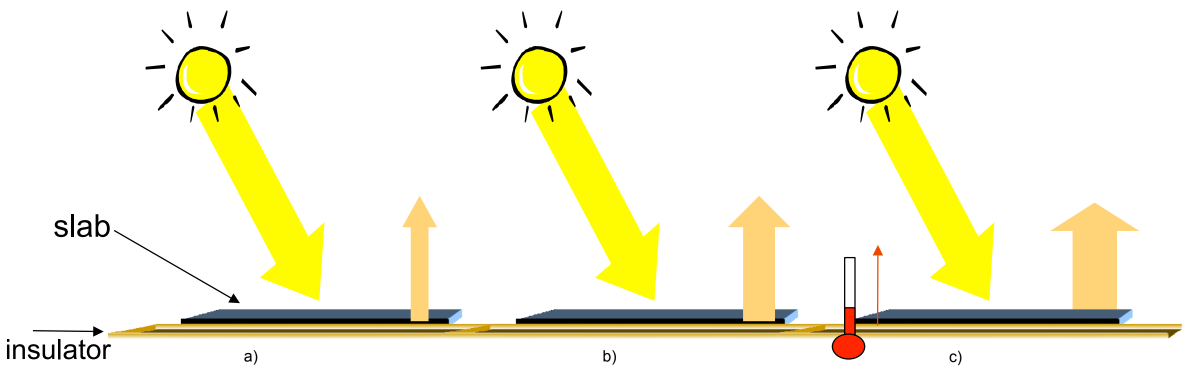
$$\text{Albedo} = \frac{\text{radiation reflected by the Earth}}{\text{solar radiation received by the Earth}}$$

The Earth albedo is about 30%

- *Clouds: 20%*
- *Molecules: 6%*
- *Surfaces : 4%*
    - *ice sheet : 60 to 92%*
    - *oceans : 5%*
    - *vegetation : 10 to 20%*



Temperature of Equilibrium

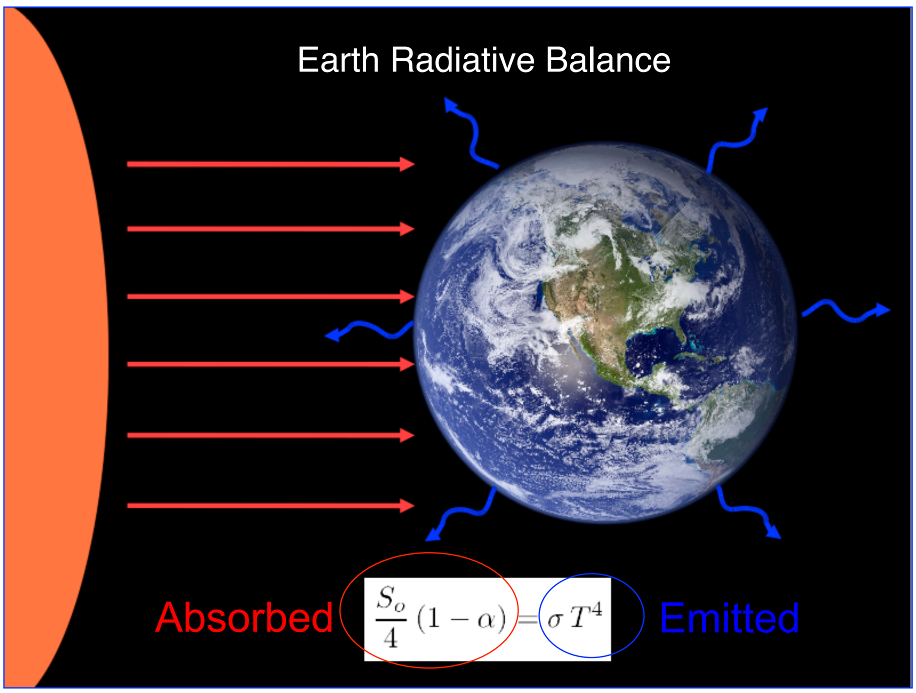


When an object receives more energy than it emits, its temperature increases

As its temperature increases, the energy lost by emission of radiation increases

Equilibrium occurs when the energy lost by the object is exactly compensated by the energy received by the object

Radiative Budget and Greenhouse Effect



S_o = Solar constant
α = Earth albedo
T = Earth temperature

$$\frac{S_0(1-\alpha)}{4} = \sigma . T^4$$

Mean albedo of the Earth = 30%
Solar constant S_0= 1370 W
σ = Stefan-Boltzmann constant

$\Rightarrow$T = 255K = -18°C

In reality, the mean Temperature of the Earth is about 15°C (288K)… because of the Greenhouse Effect

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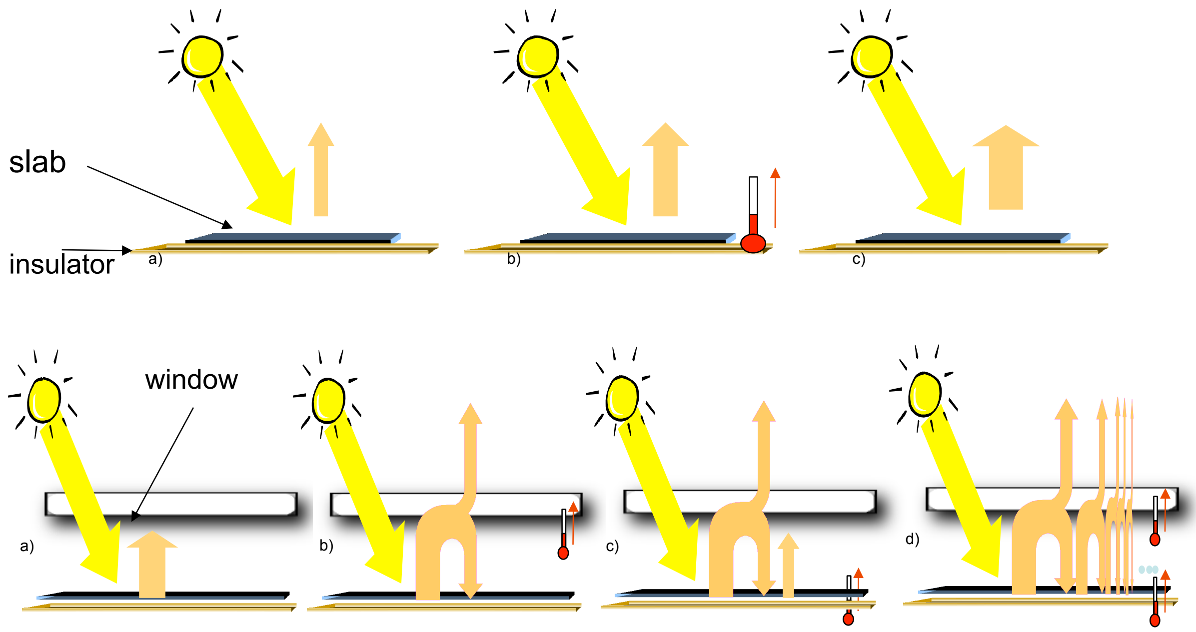
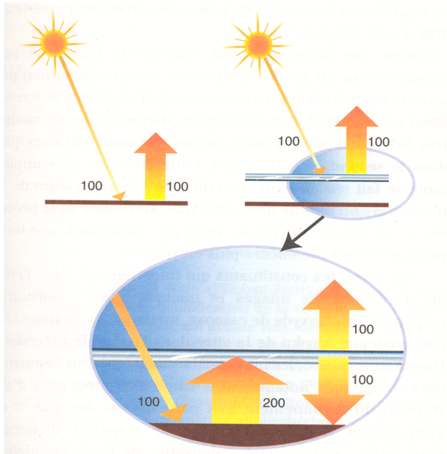
2) Greenhouse effect

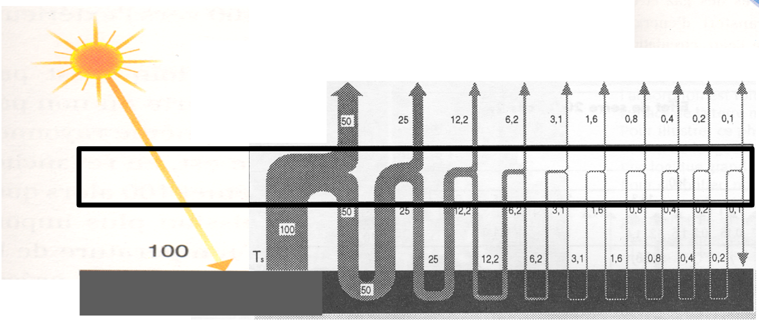
Greenhouse effect : principle



Greenhouse effect : principle

A window transparent to sunlight (shortwaves) and opaque to long-wave radiation (emitted by ground) is exposed to sunlight

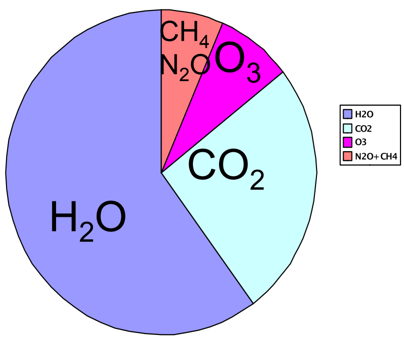




Greenhouse effect: contribution of atmospheric gases

Contribution of atmospheric gases to
the natural greenhouse effect

Water vapor	60%
CO_2	26%
Ozone O_3	8%
$N_2O + CH_4$	6%



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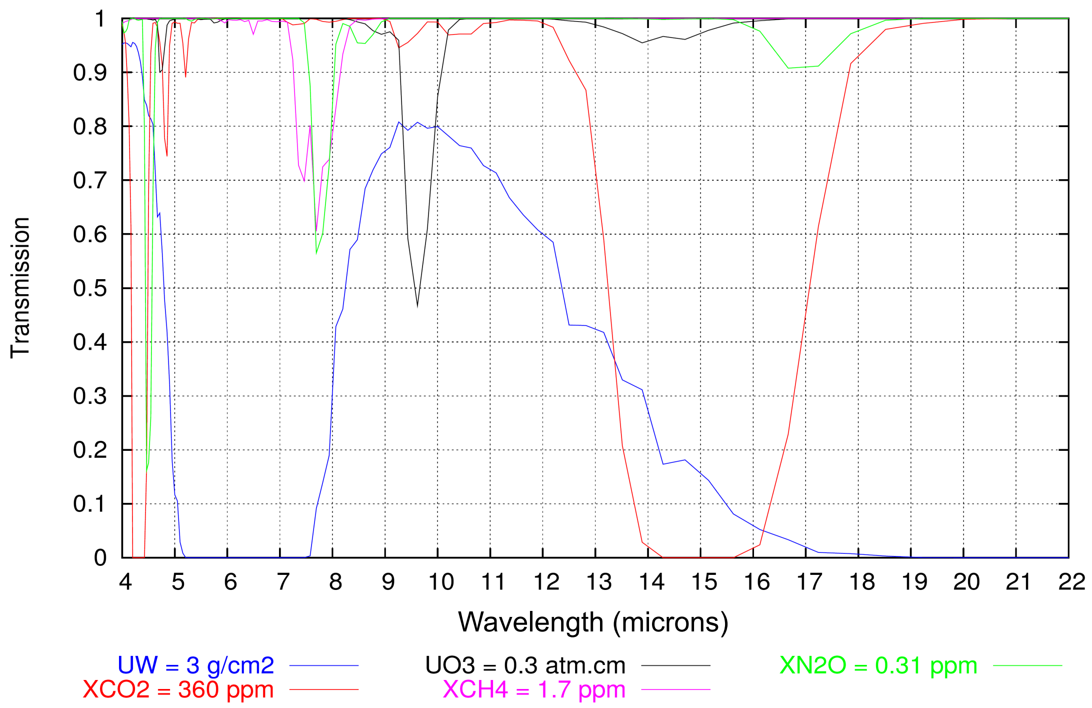
Transmission of radiation emitted by the ground by some greenhouse-effect gases



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Climate change: a theoretical prediction

19st century: discovery of the “greenhouse effect in the atmosphere”

J. Fourier

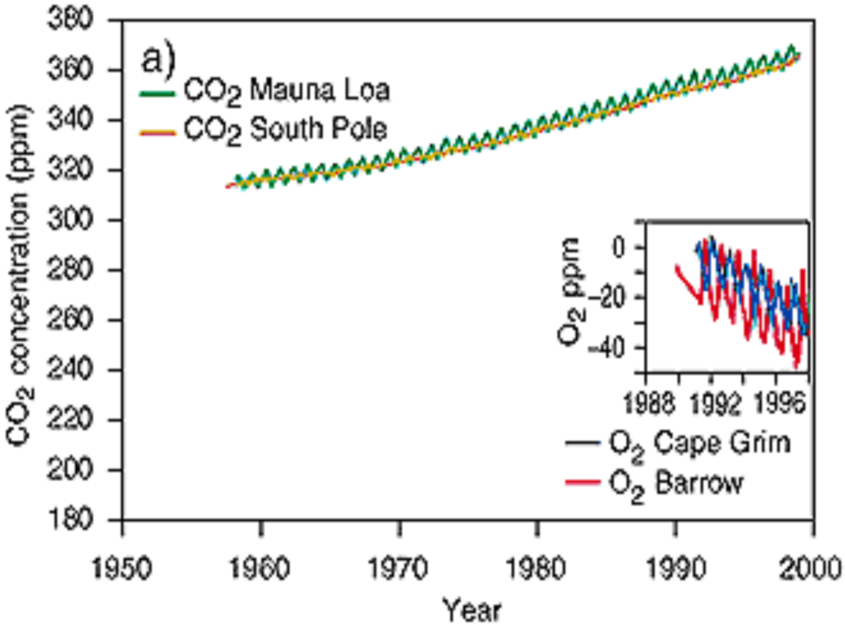
Beginning of 20st century: hypothesis:

- changes in CO_2 in the past may have influenced the climate
- human activities could imply an increase of atmospheric CO_2, which may modify the Earth climate

S. Arrhenius

Radiative Budget and Greenhouse Effect

Observations of CO_2 concentrations are relatively recent

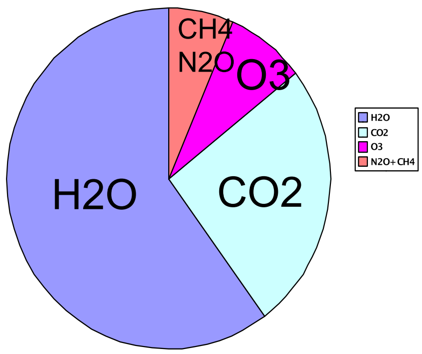


Mauna Loa: Hawaii
South Pole: air bubbles in ice

Radiative Budget and Greenhouse Effect

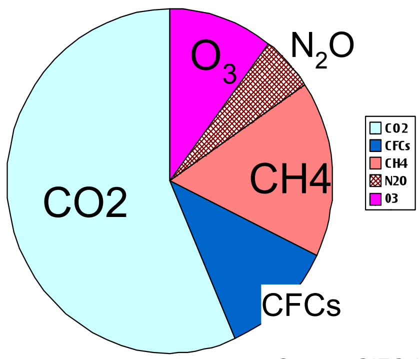
Natural Greenhouse effect:

Water vapor	60%
CO_2	26%
Ozone O_3	8%
N_2O+CH_4	6%



Contributions to the Greenhouse effect
increase from human activity

CO_2	56%
CFCs	12%
Methane (CH_4)	16%
Ozone (O_3)	11%
N_2O	5%



Source: GIEC 2007

3) Earth radiative budget

Earth Radiative Budget:

Q = Received Radiation – Emitted Radiation

Global mean over a year: Q=0

but strong spatio-temporal variability

Positive radiative budget: Q > 0

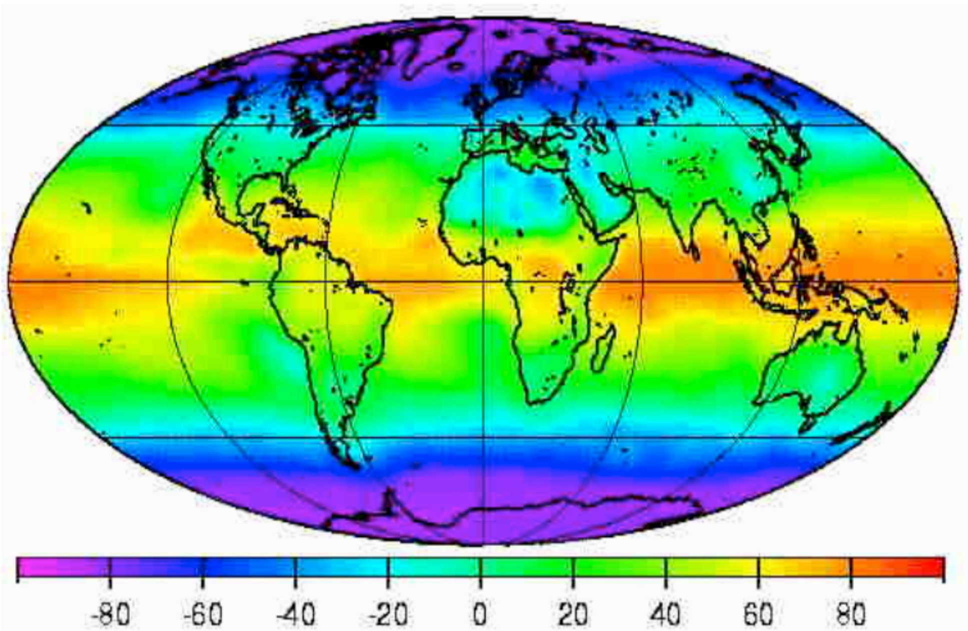
=> Received radiation > Emitted radiation => warming

Negative radiative budget: Q < 0

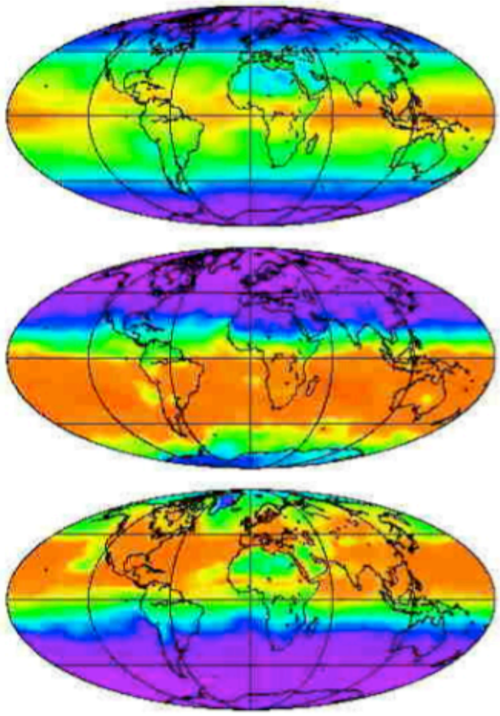
=> Received radiation < Emitted radiation => cooling

Radiative Budget and Greenhouse Effect

Radiative budget at the top of the atmosphere (in W/m^2)



Seasonal variation of the Earth radiative budget at the top of the atmosphere



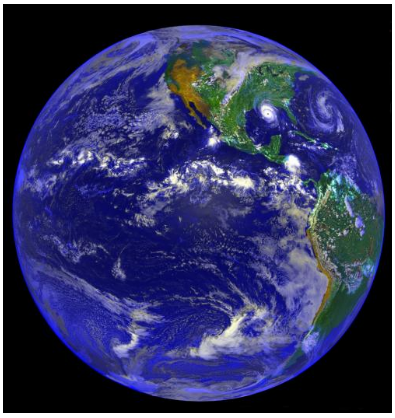
Radiative Budget and Greenhouse Effect

[About the Earth radiative budget at the top of the atmosphere:]

The subtropical deserts emit more radiation than they receive => these regions strongly warmed by the sun, are, in average …cooled

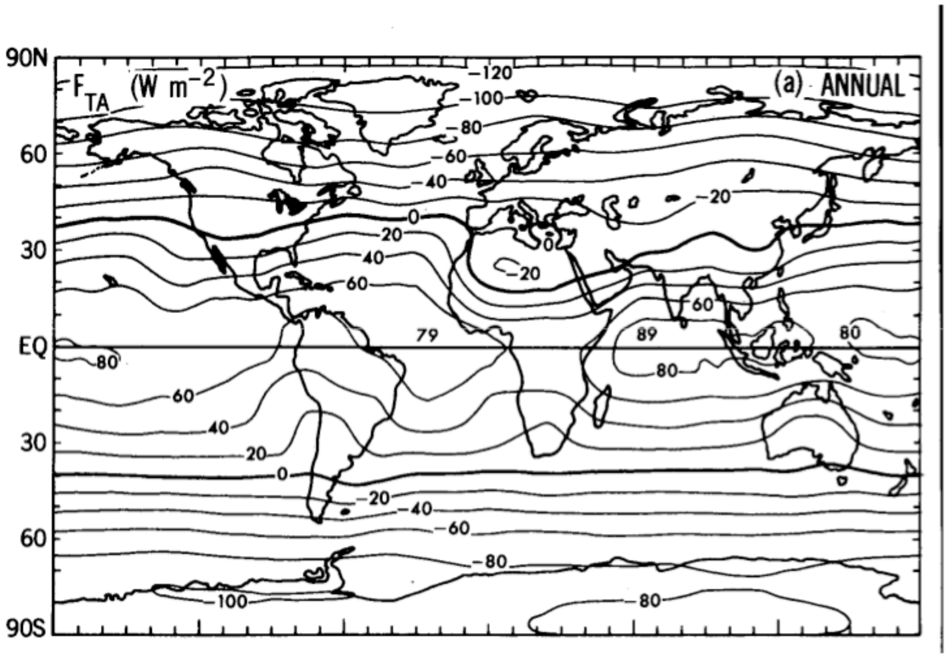
The two fluid envelopes of the planet (ocean and atmosphere) redistribute the energy: this attenuates the geographical and seasonal differences

The zonal mean (in latitude) radiative budget allows to determine the amount of heat transported by the ensemble ocean-atmosphere

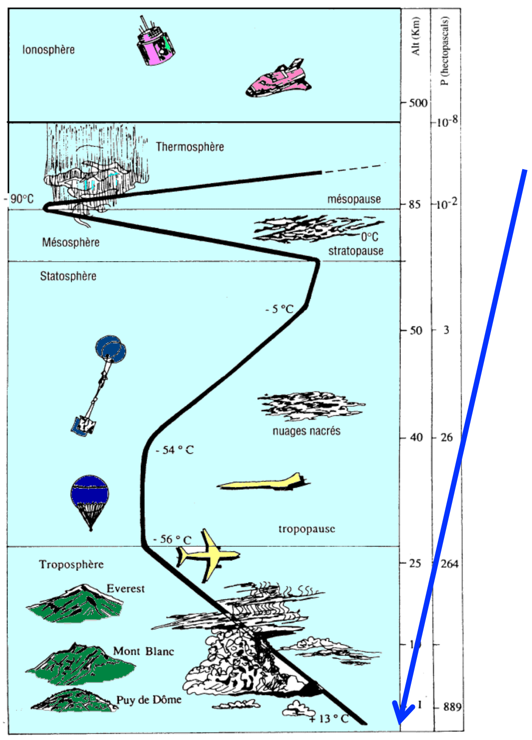


Radiative Budget and Greenhouse Effect

Earth radiative budget at the surface



Radiative Budget and Greenhouse Effect



[About the Earth radiative budget at the surface:]()

The Earth radiative budget at the surface is positive in annual global mean => warming

The Earth radiative budget at the surface is negative during the night => cooling

The *energetic radiative budget (difference of radiative budget)* at the surface cancels due to fluxes carrying latent heat and sensible heat

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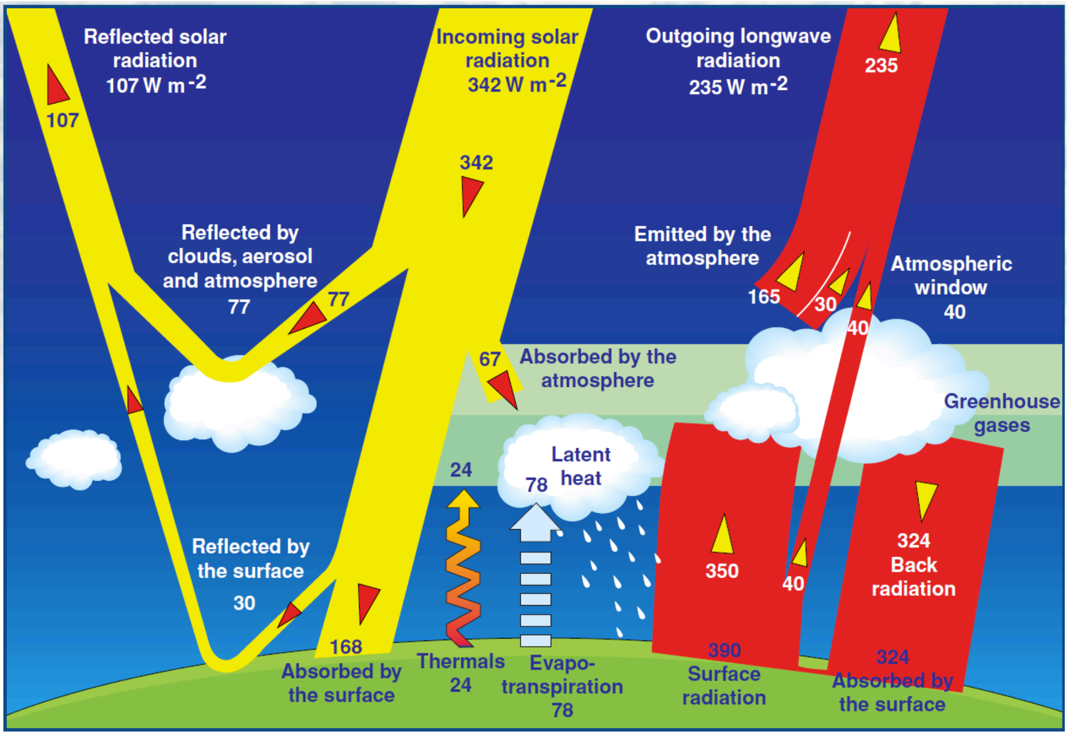

Radiation Balance of the Earth (Jeffrey T. Kiehl and Kevin Trenberth)

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Earth radiative budget : orders of magnitudes

Short-wave radiations

The Earth receives and re-emits 342 W/m²

- 30% (107 W/m²) is reflected towards space => albedo
- 20% is absorbed by the atmosphere
- 50% (168 W/m²) reaches the surface (oceans +continents)

Long-wave radiations

- The surface receives 324 W/m² through long-wave radiation (from water, gases, clouds…) in addition to the 168 W/m² from solar radiation
- The surface re-emits 390 W/m²

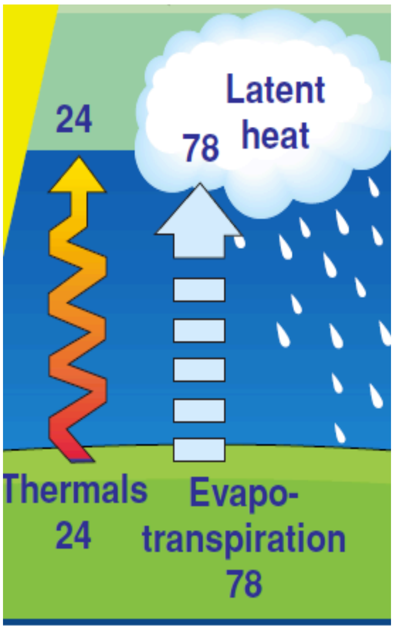
- The excess contributes to evaporate water (78 W/m²) and warm low atmospheric layers (24 W/m²)

Non-radiative energy exchanges at the surface

<u>Two mechanisms cool the surface:</u>

Sensible heat flux: cools the surface and warms the atmosphere by thermic convection (24 W/m^2); the warmed air rises, air is permanently renewed at the surface

Latent heat flux: linked to water evaporation (78 W/m^2). Evaporation cools the surface and the corresponding energy is regained later by the atmosphere when water vapor condenses to form clouds.



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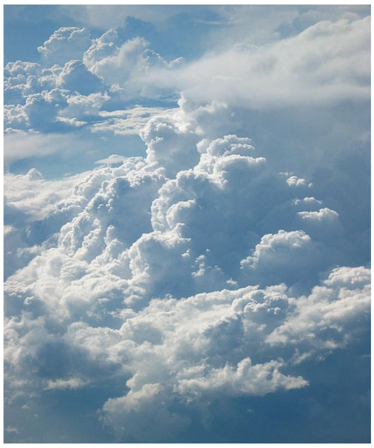
Main modulators of the Earth radiative budget



Temperature:
at the surface and vertical gradient in the atmosphere

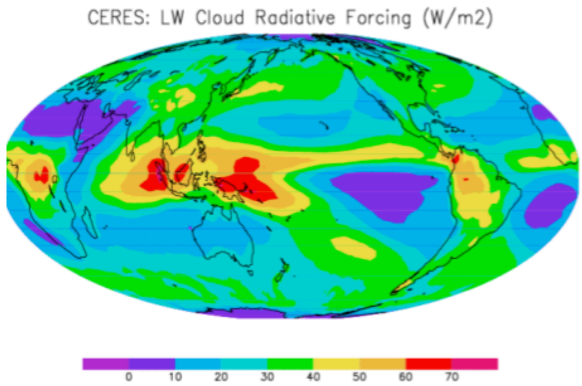
Water vapor:
main greenhouse gas in the terrestrial atmosphere

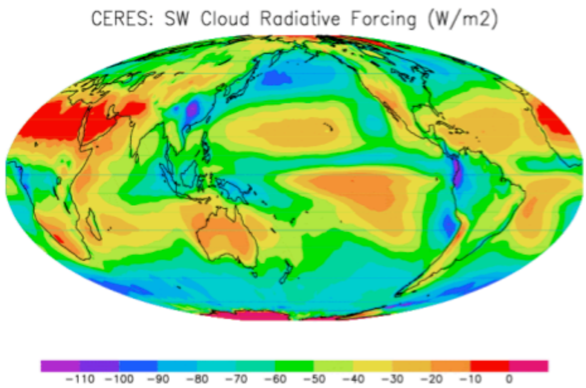
Ice-sheet and snow:
contribution to the albedo

Clouds:
antagonist effects in the long-wave and short-wave
=> contribute to both warming and cooling

The modulation of radiative budget by clouds

Cloud radiative forcing = $F_{\text{in absence of cloud}} - F_{\text{in presence of cloud}}$





Long-wave:
Clouds contribute to greenhouse effect

Short-wave:
Clouds contribute to the Earth's albedo

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4) Very simple formulation of the radiative budget

a) Without atmosphere

Earth surface ———————— T

Radiation received by the Earth = $S \pi R^2$.
Radiation emitted by the Earth = $\sigma T^4 \, 4 \pi R^2$
Radiation reflected by the Earh = $S \pi R^2 \alpha$

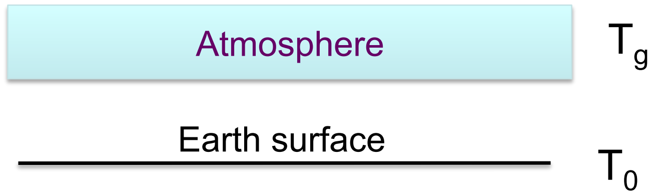
Equilibrium => $S(1-\alpha) = 4\sigma T^4$ => T= 255K = -18°C

σ = Stefan-Boltzman constant = 0,567 10^{-7} $Wm^{-2}K^{-4}$
S = Solar constant = 1370 ± 4 Wm^{-2}
R = Earth radius
α = Earth mean albedo = 0.30

Radiative Budget and Greenhouse Effect

b) With atmosphere

Atmosphere = a gaz layer transparent for solar radiation which **absorbs all the longwave** radiation emitted by the Earth



received — emitted

Equlibrium at the surface: $(\pi R^2)[S(1-\alpha) + 4\sigma T_g^4] = \sigma T_o^4 (4\pi R^2)$

Equilibrium at the level of the gaz layer: $\sigma T_o^4 (4\pi R^2) = 2\sigma T_g^4 (4\pi R^2)$

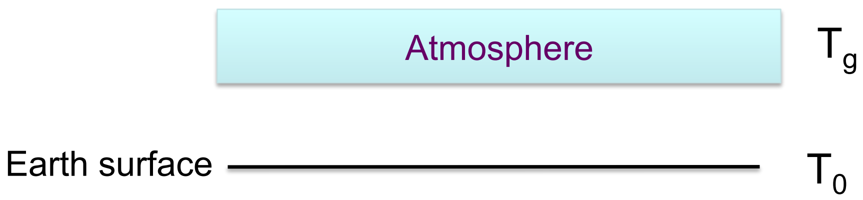
=> $T_0^4 = 2T_g^4$ and $S(1-\alpha) = 2\sigma T_0^4$ => T_0= 302K = 29°C

Radiative Budget and Greenhouse Effect

b) With atmosphere

Atmosphere = a gaz layer transparent for solar radiation and **semi –transparent to longwave** radiation emitted by the Earth

=> Budyko (1969) used observations (which contain greehouse effect) to built an empirical relationship between the longwave radiation and the temperature: $(\sigma T_o^4) \rightarrow (A+BT_0)$ with A=203.3 Wm^{-2} and B= 2.09 $Wm^{-2} K^{-1}$



received — emitted

Equlibrium at the surface: $(\pi R^2)[S(1-\alpha) + 4\sigma T_g^4] = (A+BT_0)(4\pi R^2)$

Equilibrium at the level of the gaz layer: $(A+BT_0)(4\pi R^2) = 2\sigma T_g^4 (4\pi R^2)$

=> T_0= 288 K = 15°C

Radiative Budget and Greenhouse Effect

Concluding Remarks

A rigorous computation of the Earth greenhouse effect requires to take into account the vertical gradient of temperature in the atmosphere (not treated in this course) instead of a simple 2 layers models.

An estimation of the variation of temperature in response to a perturbation (like CO2 increase) requires to take into account the various climate feedbacks (not treated in this course):

- a positive feedback increases the initial temperature perturbation
- a negative feedback decreases the initial temperature perturbation

Today, there is no theory allowing to estimate these various feedbacks, that is why climate scientists need to use numerical climate models.

Radiative Budget and Greenhouse Effect

RADIATIVE BUDGET AND GREEN-HOUSE EFFECT
– PRACTICAL CLASSES –

Hélène Chepfer (chepfer@lmd.polytechnique.fr) – Short-wave radiation Part
Marjolaine Chiriaco (marjolaine.chiriaco@latmos.ipsl.fr) – Long-wave radiation Part
Vincent Noel (noel@lmd.polytechnique.fr) – Short-wave radiation Part

I. Short-wave radiation class

I.1. Introduction

Solar radiation is mostly short-wave. Part of it is reflected by clouds, surfaces, deserts, ice-sheets… The Earth albedo is defined as the ratio between the short-wave radiation entering the Earth system at the "top of the atmosphere" (typically around 30 km of altitude) and the short-wave radiation coming out of the Earth system, after being reflected (by clouds, etc.) The average Earth global albedo over a year is about 30%. The albedo effect contributes to cool the Earth temperature. The albedo and its cooling effect depend on several variables: the season and the latitude (through the angle of incidence of solar light on Earth), the capacity of the ground surface to reflect solar light (e.g. oceanic surfaces absorb more than 95% of solar light and therefore reflect less than 5%), and the opacity of clouds and aerosols which modulate the amount of solar light reflected up to the top of the atmosphere or transmitted to the ground.
The goal of your work today is (i) to see the orders of magnitude of short-wave radiation that enter the Earth system and reach the ground, (ii) to understand short-wave radiation variability with season, latitude, and cloud opacity, (iii) to understand the albedo effect.

I.2. What you have to do

(1) Experiment
Observe how short-wave radiations are measured by SIRTA instruments.

(2) Analyse your measurements

- Plot the time evolution of short-wave radiation measured today (global, direct and diffuse), and the solar angle. You can also look at the temperature. *You can use radflux_sw_day program.*
- How does it change with time?
- What would this plot look like in clear-sky conditions (i.e. no cloud or aerosol)? Plot the clear sky radiative flux with the appropriate options and try to understand with which equation it has been calculated (based on your morning lecture). Same question for the radiative forcing.
- What are the "direct" and "diffuse" short-wave radiations reaching the ground?
- How do clouds and/or aerosols affect today's observations? Note the orders of magnitude. Do today's clouds and/or aerosols contribute significantly to atmospheric cooling?

(3) Analyse long-term SIRTA measurements

- Plot the time evolution of short-wave radiation (global, direct and diffuse) measured during one year (2008) at SIRTA, and the solar angle. *You can use radflux_sw_year program.*

- How and why does it change with seasons? Note the order of magnitude of this variability.
- Which season is more cloudy?
- Plot the clear sky flux and the radiative forcing with the appropriate options. In which season is it stronger?

(4) Analyse space-borne short-wave measurements

- Plot the short-wave radiation observed from satellite at a global scale. *You can use radflux_sw_map program.*
- What are the differences between short-wave radiation observed from the ground (SIRTA) and from space? Why are both measurements necessary?
- Note the order of magnitude of short-wave radiation observed from satellite. Compare with ground observations (SIRTA). Explain the differences.
- Why does the short-wave radiation observed from satellite vary with latitude?
- Observe the effects of clouds, deserts, ice-sheets on short-wave radiation observed from satellite.
- Plot the short-wave clear sky flux and radiative forcing at the top of the atmosphere. What does it teach us on the cooling of the atmosphere?

Computing tools

- *open a "terminal": click on the small screen icon*
- *open the Matlab tool: write "matlab" in the terminal and "enter"*
- *open the good program: write the name of the program and "enter":*
    i. ***radflux_sw_day*** *to plot figures for the current day; you can plot the good file by clicking on the "open" button; You can plot the clear sky;*
    ii. ***radflux_sw_year*** *to plot figures for a complete year; you can chose the year you want to plot by clicking on the "open" button; you can also plot the temperature and/or the solar angle by clicking on the "data" button; you can plot the clear sky and the radiative forcing;*
    iii. ***radflux_sw_map*** *to plot figures from satellite measurements; use the button to chose the year you want to plot, and the clear sky fluxes and radiative forcing.*

<u>I.3. Questions specific to short-wave radiation</u>

Question I.A
How are short-wave radiations measured?

Question I.B
Which variables govern the short-wave radiation variability? Use results from your analyses to answer this question.

Question I.C
What is the albedo effect? What are its primary consequences for life on Earth?

I.4 Discussion and conclusion

Answer these questions after joining the two groups, and make a power-point synthesis (you can use the example *mask.ppt*).

Question I-II.D
Which variables and components of the Earth system drive the long-wave radiative forcing and the short-wave radiative forcing? Quantify the effects of the most important components. Compare their effects on long-wave and short-wave radiative forcings. How does each of these forcings affect the temperature on Earth? How do their effects combine?

Question I-II.E
Do quantities that describe the radiative budget and the greenhouse effect seem to you well-known and measured? Do measurement errors seem significant? Do you think the radiative budget and the greenhouse effect are still a source of uncertainty for climate prediction, and why?

II. Long-wave radiation class

II.1. Introduction

Solar radiation is mostly short-wave. A part of it is absorbed by the Earth and atmospheric components (water vapour, clouds, anthropogenic gases), which heat up and re-emit long-wave radiations (= infrared radiations) in all directions. Parts of these new radiations are again absorbed by the Earth and atmospheric components, which heat up and re-emit new long-wave radiations. Some is absorbed by the ground, leading to ground heating. This is the greenhouse effect, and without it, the Earth mean temperature would be about -18°C.
Water vapour is the most important greenhouse effect gas, and if we also consider clouds, atmospheric water represents the major part of greenhouse effect.
The goal of your work today is to understand how water vapour, clouds, and anthropogenic gases affect the ground temperature through long-wave radiations. For that, you will (1) study a few hours of long-wave radiations measurements (using your own experiment), (2) study long-time series of long-wave radiations measurements at SIRTA from the same kind of experiment, (3) study satellite data of long-wave fluxes in order to understand what happens at global scale.

II.2. What you have to do

(1) Experiment

Observe how long-wave radiations are measured by SIRTA instruments.

(2) Analyse your measurements

- Plot the time evolution of the long-wave flux measured today, and the associated temperature and solar angle. *You can use radflux_lw_day program.*
- How does it change with time?
- Can you say that the long-wave flux is correlated to the solar angle? And to the temperature? In witch way?
- Can you explain the figures using your own observation of the sky today?
- What would this plot look like in clear-sky conditions (i.e. no cloud or aerosol)? Plot the clear sky radiative flux with the appropriate options and try to understand with which equation it has been calculated (based on your morning lecture). Same question for the radiative forcing.

(3) Analyse long-term SIRTA measurements

- Plot the time evolution of the long-wave flux in 2008, and the associated temperature. *You can use radflux_lw_year program.*
- Can you differentiate each season?
- How is the long-wave flux correlated to the temperature?
- Are you able to identify cloudy situations? Clear sky situations?
- Define the long-wave radiative forcing and plot it with the appropriate options. Try to interpret the figures.

(4) Analyse space-borne long-wave measurements

- Plot the global map of the long-wave flux in 2009, one map for each season. You will need to adapt the colour scale depending on what you want to highlight. *You can use radflux_lw_map program.*

- Do the same for the long-wave clear sky flux and radiative forcing.
- What can you say about the latitudinal variation of the fluxes? How can you explain it?
- Same question but for the seasonal variation.

Computing tools

- *open a "terminal": click on the small screen icon*
- *open the Matlab tool: write "matlab" in the terminal and "enter"*
- *open the good program: write the name of the program and "enter":*
    i. ***radflux_lw_day*** *to plot figures for the current day; you can plot the good file by clicking on the "open" button; You can plot the clear sky;*
    ii. ***radflux_lw_year*** *to plot figures for a complete year; you can chose the year you want to plot by clicking on the "open" button; you can also plot the temperature and/or the solar angle by clicking on the "data" button; you can plot the clear sky and the radiative forcing;*
    iii. ***radflux_lw_map*** *to plot figures from satellite measurements; use the button to chose the year you want to plot, and the clear sky fluxes and radiative forcing.*

II.3. Questions specific to long-wave radiation

Question II.A
How are long-wave radiations measured?

Question II.B
What are the variables that govern long-wave radiations variability? Use your results to answer this question, for example with the order of magnitude for the present day.

Question II.C
Explain what the greenhouse effect is, using your results. What are its primary consequences for life on Earth?

II.4 Discussion and conclusion

Answer these questions after joining the two groups, and make a power-point synthesis (you can use the example *mask.ppt*).

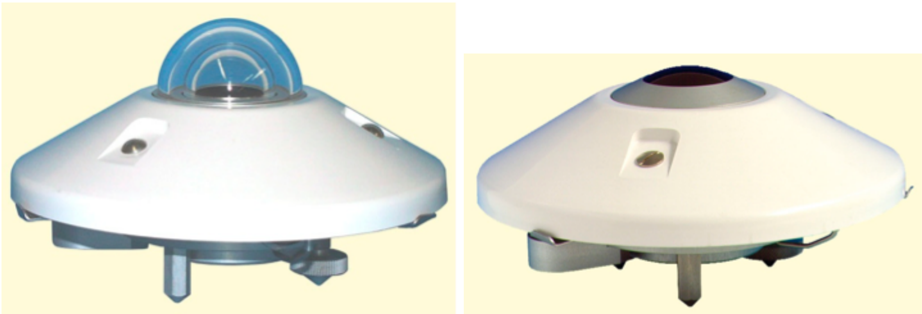
Question I-II.D
Which variables and components of the Earth system drive the long-wave radiative forcing? The short-wave? Quantify the effects of the most important components. Compare their effects on long-wave and short-wave radiative forcings. How does each of these forcings affect the temperature on Earth? How do their effects combine?

Question I-II.E
Do quantities that describe the radiative budget and the greenhouse effect seem to you well-known and measured? Do measurement errors seem significant? Do you think the radiative budget and the greenhouse effect are still a source of uncertainty for climate prediction, and why?

Instruments

As part of the SIRTA (*Site Instrumental de Recherche par Télédétection Atmosphérique*) observation activities, long-wave and short-wave downwelling radiations at the surface are routinely measured since 2002 using:

- one pyranometer (0.3 to 3µm) for solar diffuse flux
- one pyranometer (0.3 to 3µm) for solar global flux
- one pyrhéliometer (0.3 to 3 µm) for solar direct flux
- one pyrgeometer (4 to 40 µm) for infrared flux



Global and diffuse radiometer (left) used to measure short-wave radiation and Infrared radiometer (right) used to measure long-wave radiation

This station is part of the international measurement network BSRN (*Baseline Surface Radiation Network*, *http://www.bsrn.awi.de/*), which involves 40 similar stations.

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